Abstract

Top-down and bottom-up models have been used to sustain climate policy decisions and evaluate the costs of achieving a certain level of abatement. However, due to their different concepts the costs estimated by the two approaches usually differ, with top-down calculating higher costs. These divergences can also contribute to the definition of different strategies of reduction based on the model results. This paper explores this issue by illustrating whether two harmonized bottom-up and top-down models, applied to the same region, i.e. Portugal, and with the same climate policy scenario, can lead or not to different approaches for carbon abatement and climate policies. The Portuguese economic and energy system was used as a case-study, and the bottom-up model TIMES_PT and the computed general equilibrium model (top-down) GEM-E3_PT were used to generate a post-Kyoto scenario regarding progressive CO\textsubscript{2} caps from 2020 to 2050. To ensure that the models represent the same reality an inter-calibration process in a Baseline Scenario (in the absence of climate policies) was performed, calibrating sectoral energy consumption and emissions. Results show that for lower reduction efforts, which can be met without significant changes in the energy system structure, the models indicate the same strategy regarding the CO\textsubscript{2} emissions included in European Emissions Trading System (EU-ETS) (energy supply and industry) and in non EU-ETS (agriculture, transport, residential and commercial). However, for more restrictive caps and at sectoral level, significant differences can be observed. In 2050 TIMES_PT induces a higher relative effort in the non EU-ETS sector supported by transport sector while GEM-E3_PT maintains the EU-ETS sector as the main reduction sectoral group, due to electricity reduction effort. These differences have implications especially if a burden-sharing agreement is being considered, inducing policy makers to select dissimilar sectoral policies for mitigation.

Keywords

Top-down model, bottom-up model, CO\textsubscript{2} reduction

1. Introduction

Climate change is currently acknowledged by policy makers and the scientific community as one of the major challenges faced by mankind. Its long-term impacts can affect human development in a decisive way, changing available resources, the pace of economic activities, life-styles and well being. Thus, significant efforts are being developed on the identification and implementation of greenhouse gases (GHG) emissions mitigation policies and measures, both at national and supra-national level, e.g. the European Union (EU).

Numerous energy-economic-environmental models have been developed to support these mitigation options, such as bottom-up and top-down models, which are the most common modeling tools.

Conventional bottom-up (BU) models follow a partial equilibrium representation of the energy system, describing it in great detail in a form of technology matrix containing current and future technologies. They solve optimization problems, computing the least-cost combination of energy technologies to meet energy service demand subject to several restrictions (e.g. emissions, technologies availability, energy sources potential). Energy services demands can be dependent of their own generated cost, through exogenously given price-elasticities.
However BU models neglect the interactions of the energy sector with the rest of the economy, ignoring the macroeconomic feedbacks of different energy system pathways induced by the climate change policies. Moreover they represent the behavior of the economic agents in a rather simple way taking into account only explicit cost elements. When the technologies costs in different time periods are converted into present value using a social discount rate, many emerging technologies appear to be profitable. Still, for the economic agents they may not be perfect substitutes of the existing ones, requiring additional incentives before adoption (Rivers and Jaccard, 2005).

Conventional top-down (TD) models, especially Computable General Equilibrium (CGE) models, are also used in energy policy assessments. CGE models describe the interaction between the energy system and the economy as a whole, following Arrow-Debreu economic equilibrium paradigm (Shoven and Whalley, 1992), maximizing the utility of the economic agents as a sequence of optimal savings, investment, and consumption decisions. Nevertheless, these models do not contain technological detail, representing the energy sector in aggregate form by production functions which capture substitution possibilities through elasticities of substitution (Böhringer, 1998).

Good estimates for these parameters are decisive for a correct evaluation of policy strategies, but normally substitution elasticities for single countries and energy sectors are rare (Böhringer, 1998) and are estimated from aggregate historical data, which do not guarantee that these parameter values can be applicable in the future under the adoption of climate policies.

Although both model approaches contribute to assess carbon mitigation options, their results have tended to diverge, with TD models estimating higher GHG abatement costs (Grubb et al., 1993; Wilson and Swisher, 1993; IPCC, 2001; IPCC, 2007). Since TD models do not contain technological detail, they overestimate the economic adjustments and do not take well into account possible technological changes that can be induced by price adjustments associated with energy-related GHG emissions abatement. This way, TD models tend to suggest that the efforts to change the energy system away from today’s structure would be excessively costly (Hourcade et al., 2006). On the other hand, because BU models ignore the macro-economic feedbacks of different energy/climate policies, they indicate that environmental goals can be reached at an excessive lower cost. Both models use a simplified approach to represent the behavior of consumers and suppliers.

Policy makers need clear and consistent information concerning the better strategies to reduce GHG, the real impact of policies in the economy and their effectiveness to reduce emissions. Thus, these divergences between the models’ behavior can generate different strategies for carbon reduction, which result in uncertainty for decision-makers and question the model value for assisting the design of policy instruments. Even though some studies (Grubb et al., 1993; Wilson and Swisher, 1993; IPCC, 2001; IPCC, 2007) have confronted the results of top-down and bottom-up approaches under carbon mitigation options they frequently focus on the marginal mitigation costs and give little attention to the different sectoral reduction strategies defined by the two models and/or lack in consistency between the scenario assumptions, mainly different baseline scenarios which influence the interpretation of the results.

This paper explores this issue by illustrating whether two inter-calibrated BU and TD models, applied to the same region, i.e. Portugal, and to a climate policy scenario, can lead or not to different approaches for carbon abatement and thus impact on the development of climate policies, for example, by imposing different sectors reduction or/and strategies for mitigation. Therefore, the two models were subject to Post-Kyoto scenario regarding increasing CO₂ caps from 2020 to 2050.

Section 2 is devoted to present an overview of the models used in this paper: the BU TIMES_PT and the CGE GEM-E3_PT. Section 3 discusses in detail the calibration process between the two models. Section 4 outlines the mitigation policy used and Section 5 shows the results from both models, comparing their outcomes and illustrating the differences between them in terms of carbon mitigation strategies. The main conclusions from this analysis are discussed and summarized in Section 6.
2. Models overview

GEM-E3 Model

GEM-E3 (General Equilibrium Model for Economy, Energy, Environment) is a multi-region, multi-sector, dynamic, computable general equilibrium model developed by an European consortium of universities and research institutes and funded by the Commission of the European Communities\(^1\). The model represents 21 world regions (GEM-E3 World) or 24 European countries (GEM-E3 Europe), depending of the version, characterizing its macro-economy and interactions with the energy system and environment (Capros et al., 1997 and www.gem-e3.net).

Based in microeconomic theory and adopting the quantitative application of the Arrow-Debreu economic paradigm, GEM-E3 computes the equilibrium prices of goods, services, labor and capital that simultaneously clear all markets and optimize the behavior of the economic agents. Being a recursive dynamic model, GEM-E3 is solved for a sequence of static equilibriums over time periods, connected by the accumulation of capital and equipment.

The model incorporates the economic behavior of 4 agents: consumers, firms, government and foreign sector, although the consumption and investment of the government is exogenous as well as the foreign sector behavior in the single country version. Consumers represented by households, choose between present and future consumption of goods/services, leisure and savings, in order to maximize their inter-temporal utility function subject to an inter-temporal budget constraint related to the level of income, but sustained by myopic expectations. In GEM-E3 households can allocate their consumption expenditure between eleven non-durable consumption commodities, such as, food, cloths, health services, culture or two durable goods (heating systems/electric appliances and transport equipment). Simultaneously, producers represented by firms assume short-term profit maximization by deciding the level of production, according to selling and production factors prices and under the restriction of their production technologies.

The model assumes 18 productive sectors or activities (Table 3 presents some sectors), that combine primary factors (capital and labor) with intermediate consumption of materials, services and energy (coal, oil, natural gas and electricity) to determine a level of output.

Following the same structure of the standard World Bank models, GEM-E3 is built on basis of a Social Account Matrix (SAM), covering the economic structure of each region or country assuming production, investment, final consumption by households and government and the transfers between the economic agents. Additionally, the model contains an environmental module, which considers energy related atmospheric emissions. The emissions linked to energy consumption are computed through exogenous emission factors.

GEM-E3 results include detailed Input-Output (IO) matrixes by region, employment, GDP, household and government consumption, energy use and supply, among other parameters. A more detailed description of the model and its equations can be seen in www.gem-e3.net.

GEM-E3-PT corresponds to a single country version of GEM-E3, characterizing the Portuguese economic structure from 2000 to 2050 in 5 years time steps. The 2000 benchmark SAM was built from Use and Supply IO tables, published by Eurostat (Eurostat, 2007) and the transfers between sectors from the Portuguese National Accounts distributed by the National Statistic Institute (INE, 2008). The national nomenclature data (NACE 60 PRODUCTS) was adjust to be consistent with GEM-E3 structure (18 sectors and 13 consumption categories) through the aggregation and disaggregation of some sectors and categories. Additional data such as Gross Fixed Capital Formation and Households consumption was also used to estimate the investment and consumption matrix, respectively.

The energy demand in value from the 2000 SAM was converted in physical energy consumption (PJ) by crossing the energy balances from the National Directorate for Energy and Geology (DGEG) (DGGE, 2007) with the energy prices published by International Energy Agency (IEA, 2008a), resulting in the sectoral energy (fossil fuels and electricity) consumption in PJ. Through the use of aggregated CO\(_2\) emissions factors i.e. emissions factor for coal, oil and natural, supported by the 2000 energy balance, the CO\(_2\) generated by each productive sector and category of consumption was computed and calibrated with the national GHG submission (UNFCCC, 2008). Some contradictory information between the national accounts and the energy balance required minor adjustments in order to bring together the information from these different sources.

\(^1\) URL: www.gem-e3.net/
TIMES model

TIMES (The Integrated MARKAL-EFOM system) is a dynamic linear optimization model generator developed by ETSAP\(^2\), which simulate a regional or multiregional energy system. Based on a technology database and external constraints (e.g. GHG emissions caps, fossil fuels import prices and energy sources potential) the model computes the energy supply/demand equilibrium, where both supply and demand are adjusted to changes in prices under perfect foresight and the selling prices are the marginal cost of demand sectors (Loulou et al., 2005).

TIMES-PT maps the Portuguese energy system from 2000 to 2050 in 5 years time steps, modeling in detail the primary energy supply (petroleum refining) and electricity generation, as well as final energy consumption sectors, namely, industry, residential, commercial, agriculture and transport sectors, (see materials and energy services demand by those categories in Table 3). The model makes simultaneous decisions about equipment investment and operating, primary energy supply and energy trade (Loulou et al., 2005), computing the installed capacity of different supply and demand energy technologies, sectoral energy consumption, its energy related GHG emissions, the final energy prices and the total system costs.

In TIMES_PT energy services and materials demand are assumed having a price elasticity of -0.3 for all demands categories except for commercial cooking and public lighting, whose values were -0.2 and residential cooking with an -0.1 price elasticity. The elasticity values are generic for EU countries and were supplied by Leuven University. The technological database considered in the model includes the characteristics of the existing and future energy related technologies, such as efficiency, capacity factor, availability, technical lifetime, investment, operation and maintenance costs, etc. The data was obtained from the European NEEDS Project\(^3\) and validated by national stakeholders. More details about TIMES-PT structure, the calibration process for the year 2000, and some exogenous inputs such as national primary energy potentials, can be seen in (Simões et al., 2008).

3. Models calibration framework

GEM-E3 and TIMES have been used together in several European projects, mainly, NEEDS, and RES2020\(^4\). The connection between the two models has been made just in one way: where GEM-E3 is used to compute demand drivers, such as GDP and sectoral production growth that are converted in energy services and materials demand used as TIMES inputs.

In the present paper and to guarantee that both models are fully harmonized, a calibration process consisting in a two way iteration process was conducted within a Baseline scenario with absence of climate policies: GEM-E3_PT also considers as inputs some TIMES_PT results, namely the sectoral energy consumption profile. The overall calibration framework is presented schematically in Figure 1. In the scheme the dotted grey lines represent inputs from the Baseline scenario assumptions or calibration parameters, whereas the black lines between the models represented iteration within the calibration process. The full black lines are direct inputs/outputs and the black dashed lines represent indirect inputs.

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\(^2\) ETSAP (Energy Technology Systems Analysis Programme) is an implementing agreement of the International Energy Agency

\(^3\) NEEDS - New Energy Externalities Developments for Sustainability (www.needs-project.org).

\(^4\) RES2020 – Monitoring and Evaluation of the RES directives implementation in EU27 and policy recommendations for 2020 (www.res2020.eu/).
To achieve consistency between the two models some common variables were set equally, including:

- An annual real interest rate of 4%
- Fossil fuel import prices adopted from Reference scenario of the World Energy Outlook 2008 published by IEA (IEA, 2008b). The Reference scenario is associated with an average world GDP growth of 3.3% per year and 1.8% per year for the European Union over the period 2006-2030. Since the IEA data is only up to 2030, the prices to 2050 were determined assuming a linear trend of the past values and regarding demand forecasts, namely for coal, which it is expected to increase due to the installation of new coal power plants with carbon capture and storage, contributing to the increase of import prices. Table 1 illustrates the fossil fuel import prices considered in the present paper.

The calibration process between the two models was supported by a Baseline scenario, representing the evolution of the Portuguese economy between 2000 and 2050 without any CO₂ reduction targets. The economic assumptions of the Baseline scenario were derived from the Trend Scenario developed by the Portuguese Department of Planning, Prospective and International Relationships (DPP) (Ribeiro et al., 2008), with some adjustments like postponing the increase of the economic growth of the Portuguese economy considering more recent data.
Therefore, in an initial step, GEM-E3_PT parameters, namely technical progress on labor and materials were adjusted so that the model could compute the growth of real Gross Domestic Product (GDP) and Private Consumption considered for the Baseline Scenario. The economic outcomes presented in this paper are a fully dynamic solution of the CGE model and do not intend to be an official forecast. Moreover it does not include the current economic crisis of the Portuguese economy.

In terms of demographic growth the data from the Central Scenario within the study “Projections of the Resident Population in Portugal 2008-2060” published by the National Statistic Institute (INE, 2009) was considered. The main socio-economic drivers considered in the Baseline scenario are summarized in Table 2.

| Table 2 – Main socio-economic drivers considered in the Baseline scenario for Portugal |
|----------------------------------|---|---|---|---|---|---|
| GDP in volume (’00 M€)           | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
| 109 398.8                        | 119 228.4 | 142 640.2 | 1747 21.3 | 214 037.9 | 262 159.4 |
| Private consumption in volume    | 67 266.0 | 78 082.9 | 91 992.7 | 112 262.2 | 136 794.2 | 166 882.3 |
| Population (1000 inhab)          | 10 256 | 10 655 | 10 826 | 10 892 | 10 870 | 10 687 |
| Annual average growth rate (%)   | '00-05 | '05-10 | '10-15 | '15-20 | '20-25 | '25-30 | '30-35 | '35-40 | '40-45 | '45-50 |
| GDP (in volume)                  | 0.9% | 1.8% | 2.0% | 2.1% | 2.0% | 0.9% | 1.8% | 2.0% | 2.1% | 2.0% |
| Private consumption (in volume)  | 1.5% | 1.7% | 2.0% | 2.0% | 2.0% | 1.5% | 1.7% | 2.0% | 2.0% | 2.0% |
| Population                       | 0.6% | 0.2% | 0.2% | 0.2% | 0.1% | 0.1% | 0.0% | 0.0% | -0.2% | -0.2% |

After this stage, the calibration process between the two models followed the three steps described below and represented in Figure 1:

I. The economic drivers and energy prices generated by GEM-E3_PT were used to produce energy and materials demand according to the following equation of the demand generator (Van Regemorter and Kanudia, 2006):

\[
DEM_{j,t} = DEM_{j,t-1} \cdot \left( 1 + DRGR_{j,t} \times ELASI_j \right) \cdot \left( 1 + PRGR_{j,t} \times ELASP_j \right) \cdot (1 - AEEI_j)
\]  

(1)

DEM\(_{j,t}\) – energy demand for each energy service or material (j) in each time period (t). For the base year (2000) the energy demand was constructed considering the historic national energy consumption and the corresponded technological profile and its characteristics, namely installed capacity, efficiency, availability, among other factors;

DRGR\(_{j,t}\) – annual growth of the economic drivers from GEM-E3 and population associated with the energy service demand (Table 3 presents the correspondence between DRGR and the respective energy service or material demand TIMES’ inputs);

ELASI\(_j\) and ELASP\(_j\) – income and price elasticity for each energy service and material demand, respectively;

PRGR\(_{j,t}\) – annual growth of real sectoral energy price computed by GEM-E3;

AEEI\(_j\) – autonomous efficiency improvement factor in industrial sectors.

For the residential sector, demand was generated based on a different and more complex process, which depends on the number and characteristics of the dwellings (new or existing, single house situated in rural or urban area or multi apartment), number of persons per house, among other parameters (Simões et al., 2008).
Table 3 – Correspondence between the macroeconomic drivers (DRGR) and the respective energy service and materials demand categories

<table>
<thead>
<tr>
<th>Socio-economic drivers (DRGR) in GEM-E3_PT</th>
<th>Demand categories in TIMES_PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private consumption by household</td>
<td>Residential space heating and cooling and water heating</td>
</tr>
<tr>
<td>Private consumption as a proxy of private income</td>
<td>Residential lighting, cooking, and electricity demand for electric appliances; Road car long distance; Road moto</td>
</tr>
<tr>
<td>Domestic production of services sectors (telecommunications services, services of credit and insurances, other markets services, non market services)</td>
<td>Commercial energy demand (space heating and cooling, water heating, cooking, refrigeration and electric appliances); Public lighting</td>
</tr>
<tr>
<td>Domestic production of agriculture sector</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Domestic production of transport sector</td>
<td>Road freight; Rail freight; Aviation; Navigation</td>
</tr>
<tr>
<td>Domestic production of chemical sector</td>
<td>Ammonia; Chlorine; Other chemicals</td>
</tr>
<tr>
<td>Domestic production of energy intensive sector</td>
<td>Cement; Lime; Glass; Other non metallic minerals; Paper</td>
</tr>
<tr>
<td>Domestic production of other industries sector (electric goods, transport equipment, other industry goods industries, construction)</td>
<td>Other industries</td>
</tr>
</tbody>
</table>

II. The energy service and materials demand generated in step I was used as TIMES_PT inputs, which in turn computed the least cost technological profile of the Portuguese energy system, determining among other parameters the energy consumption (quantities per sector per energy source) and its respective CO\textsubscript{2} emissions. Although the Baseline scenario does not reflect the energy policies already defined by the Portuguese Government, as the case of renewable energy targets for 2020, some policy assumptions regarding technological availability were considered namely: (i) the ban on generation of electricity through nuclear and (ii) unavailability of carbon capture and storage technologies for the time period of analysis.

III. In GEM-E3 the energy efficiency evolution is associated with an exogenous parameter – technical progress on energy, which reduces the energy consumed by each productive sector to produce the same amount of output. In general this variable is derived from the literature, however to achieve consistency between the two models the technological progress associated to energy was indirectly copied from TIMES_PT. Therefore, the technical progress was changed until GEM-E3_PT converges to the same energy mix as TIMES_PT i.e. the fossil fuel and electricity consumption profile resulting from step II. At the same time, the GDP and private consumption values mentioned previously were maintained through slight adjustments of the technical progress on labor and materials. The step III induced both models to present the same energy consumption and align their respective sectoral CO\textsubscript{2} emissions.

Because renewable energy sources are not considered in the national accounts, GEM-E3_PT does not consider explicitly these energy sources and therefore the calibration and results assessment between the two models are focused on fossil fuels and electricity consumption. The sectoral energy consumption of GEM-E3_PT and TIMES_PT could be totally comparable with exception of the oil consumption in transport sector. In TIMES_PT the oil consumption associated with the transport activities regardless if they are developed as part of the activities of industries, services or households is included in a stand-alone transport sector. However, in GEM-E3_PT, which is supported by the national accounts, the transport sector only includes the transport industries, such as land, water and air transport services, transport via pipelines services or supporting and auxiliary transport services. All the other productive sectors that have the consumption of oil for transport associated with their activities are included in its own sector and personal road car and motorcycles are allocated to households. Therefore, the comparison of energy and CO\textsubscript{2} emissions between the two models was supported by using a constant average share of sectoral petroleum products for transport in order to determine the amount of oil associated with the transport sector as considered in TIMES_PT (Table 4).
The only exception of this process was the households sector since the oil consumption for transport is already disaggregated in the CGE model. This represents a limitation of the present analysis in the sense that the share of oil consumption for transport in each productive sector can change along the period of the analysis.

Table 4 – Share transport oil consumption in each productive sector

<table>
<thead>
<tr>
<th>Sector</th>
<th>Share of oil consumption for transport in total sectoral oil consumption from 2000 Portuguese Energy Statistics (%)</th>
<th>Share of the sector in total oil consumption for transport - assumed average from EU statistics (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>12.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Supply</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Electricity Production</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Iron and Steel</td>
<td>58.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Chemical Industries</td>
<td>22.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Energy intensive industries</td>
<td>9.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Other industries</td>
<td>37.8</td>
<td>8.1</td>
</tr>
<tr>
<td>Service sector</td>
<td>68.0</td>
<td>23.5</td>
</tr>
<tr>
<td>Transport Sector</td>
<td>100*</td>
<td>22.4*</td>
</tr>
<tr>
<td>Households</td>
<td>68.6*</td>
<td>42.5*</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

*Not used directly in the adjustment of the oil consumption for transport approach

Since modifications in the sectoral energy consumption can induce changes on the sectoral domestic production and consequently on energy services and materials demand, these three steps were repeated until total energy demand converged, i.e. achieved a minor difference relative to the previous iterative process (less than 5%).

Figure 2 and Figure 3 show the calibration results from the two models, showing that both are calibrated in the Baseline scenario regarding the sectoral fossil and electricity energy consumption e CO₂ emissions.

Figure 2 – Final and primary energy consumption by sector in PJ (Baseline scenario)
In the Baseline scenario, over the period 2005 to 2050, we observe an overall final energy consumption growth around 83% and 78% according to GEM-E3_PT and TIMES_PT respectively. The transport sector followed by industry represent together the main energy consumers with more than 70% of the total final energy consumption. Due to technological choices and an increase of energy efficiency, occurs a decline of energy consumption in transport sector from 2030 to 2040 and in industry from 2040 to 2050 in both models.

Concerning the primary energy consumption we observe an increase of 43% and 37% in 2050 in comparison to the year 2005, according to GEM-E3_PT and TIMES_PT respectively. Electricity increases its contribution to primary energy consumption from around 56% in 2005 to 72% in 2050, in both models.

In the Baseline scenario, the main combustion-related CO$_2$ source is the electricity sector followed by transport and industry. Without any emissions reduction target the electricity production is mainly sustained by coal technologies which are the cheapest. The proportion of coal in electricity generation increases from 45% in 2005 to 95% in 2050 in both models. The present simulation is not taking into account the security in energy supply and therefore energy sources diversification is not imposed to the models.

As it can be observed, both models present the same energy consumption and CO$_2$ emissions profile along the time horizon. The main difference occurs in 2050 in the supply sector, where TIMES_PT presents a primary energy consumption 9% smaller than GEM-E3_PT values. Yet the final and primary energy consumption computed from both models differ less than 3% in the total period of the analysis. Regarding the CO$_2$ emissions, the commercial sector in 2050 is responsible for the main difference between the models, with TIMES_PT presenting higher CO$_2$ emissions (9%) in this sector.

4. **Policy scenario (Post-Kyoto)**

One policy scenario was considered to analyze if the BU TIMES_PT and the CGE GEM-E3_PT can lead or not to different approaches for CO$_2$ reduction, by deciding on carbon reductions to different sectors or by assuming different strategies to achieve the environmental target.

The policy scenario (hereafter named Post-Kyoto scenario) was developed by imposing the following CO$_2$ caps on the baseline scenario based on the European Union Climate Change policy:

i) 1% increase from 2005 values of the Portuguese energy–related CO2 emissions not included in European Union GHG Emission Trading System (Non EU-ETS), set to 2020:
ii) 21% reduction from 2005 values of the Portuguese energy combustion–related CO₂ emissions included in the EU-ETS set to 2020;

iii) From 2020 onwards a linear decreasing cap was considered, reaching -60% of CO₂ emissions by 2050 compared to 1990 levels according to the EU communication “Limiting Global Climate Change to 2° Celsius: The way ahead for 2020 and beyond” (EU Commission COM(2007) 2 final, 2007): “by 2050 global emissions must be reduced by up to 50 % compared to 1990, implying reductions in developed countries of 60-80 % by 2050”. The target was imposed globally without distinction between EU-ETS and Non EU-ETS sectors.

It should be underlined that there are no national targets for the EU-ETS emissions as they will be implemented at EU level on a sector basis using benchmark data. However, due to the lack of information about the objective that will be imposed to the EU-ETS Portuguese installations it was considered the EU-ETS objective - reduce emissions by 21% of 2005 values (EU Commission COM(2008) 16 final, 2008). Moreover, the EU-ETS is applicable to each combustion installation according to its thermal input and emissions and not regarding its production sector. This means that for example in the same industrial sector, may co-exist installations included in EU-ETS and others that are not integrated. However, due to modeling limitations it was assumed that the whole industry is included in EU-ETS as well as electricity production and supply (refinery) sectors. Therefore the Non EU-ETS embraces agriculture, transport, commercial and residential sectors. Table 5 presents the CO₂ emissions associated with the Baseline scenario from each model and the correspondent CO₂ cap in Post-Kyoto scenario.

Table 5 – CO₂ energy related emissions from the Baseline scenario and the CO₂ cap from the Post-Kyoto scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CO₂ emissions (Gg CO₂)</th>
<th>2005</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline scenario</td>
<td>EU-ETS: 35 303.2</td>
<td>75 949.7</td>
<td>81 596.9</td>
<td>79 613.6</td>
<td>80 547.2</td>
<td>78 768.2</td>
<td>78 240.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non EU-ETS: 25 031.4</td>
<td>43 009.3</td>
<td>35 123.6</td>
<td>28 683.7</td>
<td>23 424.5</td>
<td>19 129.6</td>
<td>15 22.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Kyoto scenario</td>
<td>EU-ETS: 27 889.6</td>
<td>23 658.0</td>
<td>24 776.0</td>
<td>24 776.0</td>
<td>24 776.0</td>
<td>24 776.0</td>
<td>24 776.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non EU-ETS: 24 776.0</td>
<td>23 658.0</td>
<td>25 031.4</td>
<td>25 031.4</td>
<td>25 031.4</td>
<td>25 031.4</td>
<td>25 031.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Post-Kyoto caps were imposed in the two models maintaining the calibration parameters, such as, fossil fuel import prices and technological progress on energy, labor and materials.

5. Results and discussion

This section presents a number of results illustrating different model features to point out if and where the BU TIMES-PT and CGE GEM-E3_PT define different strategies for CO₂ reduction and to provide further insights about the advantage of each type of model to assess the impacts of a carbon reduction scenario. Before going into further detail the following caveats should be mentioned: i) the comparison between the two models is intrinsically limited because the BU TIMES_PT does not present macroeconomic outcomes and the CGE GEM-E3_PT does not include technological detail nor considers renewables resources explicitly as a productive factor comparable to coal or gas⁵, and ii) the outcomes do not intend to reflect the real national impact of GHG emissions reduction, because the caps are just applied to CO₂ combustion emissions and not for GHG. Thus the Post-Kyoto scenario is more demanding than the policy scenarios being debated.

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⁵The shift to renewables resources are implicitly modeled as a substitution of energy by capital.
As expected, the compliance with the Post-Kyoto scenario leads in both models to a similar decrease of the consumption of fossil energy both by end-use and energy supply sectors (Figure 4). TIMES_PT reduces fossil energy consumption by 8% in 2020 and by less than 70% in 2050, compared to 2005, whereas GEM-E3_PT achieves 9% less in 2020 and 73% less in 2050. This trend is due to an increase in renewable energy, renewable electricity and more efficient technologies in TIMES_PT and to changes in the productive structure in GEM-E3_PT, namely a substitution away from fossil energy and towards more electricity and capital, which can be interpreted as investment in renewables or/and energy efficiency. Therefore, both models follow roughly the same strategy to cope with CO2 caps, in terms of total fossil fuel consumption. It should be underlined that TIMES_PT has a 10% higher consumption of fossil fuels than GEM-E3_PT in 2050, due to different sectoral decisions as presented below.

However, it should be noted that the share of fossil fuel type in the total fossils consumption differs in the two models resulting in different reduction of CO2 intensities of fossil energy (Gg CO2/PJ): less 1 to 3%, respectively in 2020 to 2050 vis-à-vis 2005 for GEM-E3_PT and less than 4 to 10% for TIMES_PT. Figure 5 shows the CO2 intensity of fossil energy derived from the two models for the Post-Kyoto and Baseline scenarios. Even though both models reduce CO2 intensity, TIMES_PT achieves lower values than GEM-E3_PT especially in the long term, due to technological detail and flexibility that allows, from 2030 onwards, the complete substitution of coal in electricity generation for less pollutant fossil fuels, namely natural gas. GEM-E3_PT does not eliminate the coal use leading to higher CO2 intensities of fossil energy consumption beyond 2030. The differences in the share of fuels have important policy implications, mainly for power generation, as it will be analyzed later.
In both models there is a slowdown of demand growth due to the CO2 cap. In TIMES_PT the energy service and material price increase induces a reduction of total energy services and materials demand from -0.2% by 2020 to -11% by 2050 vis-à-vis the Baseline scenario. In the CGE GEM-E3_PT, demand growth has to be assessed through the evolution of several macro-economic parameters, such as GDP, private consumption and total production. Compared to the Baseline scenario, the GDP of the Post-Kyoto scenario is reduced in 0.2% to 0.1%, respectively for 2020 and 2050, while the private consumption decreases 0.2% (2020) and 0.4% (2050), and the total production of industry, agriculture and commercial decreases by 2% (2020) and 20% (2050). Considering only the total non-renewable final energy consumption, GEM-E3_PT reduces energy 20% in 2020 and 72% in 2050 from the Baseline scenario values, whereas TIMES_PT reduces only 10% in 2020 and 53% in 2050.

Figure 6 shows the CO2 mitigation potential per sector (in absolute values) defined by each model. As it can be seen in general the models indicate the same reduction structure, harvesting the main mitigation potential from the electricity generation sector, transport and industry (in 2050 these three sectors contributed with 93% of total reduction in TIMES_PT and 86% in GEM-E3_PT). These similar strategies in absolute terms are not surprising since these three sectors are the main CO2 polluters.

In order to gain further insights of the specificities of the reduction strategies of the two models it is necessary to look into the relative reductions vis-à-vis 2005 values assigned to each sector. These reproduce the reduction effort computed for each sector and translate the models’ strategy to reduce CO2.

Figure 7 depicts the results from the two models in 2020, 2030 and 2050 regarding CO2 combustion emissions variation estimated from 2005 values. The first feature is the difference between the models regarding the total EU-ETS and total Non EU-ETS reduction effort beyond 2020: (i) in 2030 both models present a similar behavior resulting in a reduction of around 34% compared to 2005 for Non EU-ETS and of 46% for EU-ETS; (ii) up to 2050, the CGE and BU models assume different strategies, with TIMES_PT allocating a stronger reduction effort for the Non EU-ETS sector (84% less than 2005 versus the 66% for EU-ETS) specially in the transport emissions, while GEM-E3_PT decides for a higher effort within the EU-ETS (81% less than 2005 versus the 62% of Non EU-ETS) mainly in the power sector. Thus, stringent reduction targets (as after 2030) require progressively more demanding strategies. In this situation the substitution elasticities of the CGE model do not allow replicating all the technological flexibility of the BU model, resulting in different solutions. The following analysis present in details the sectoral reduction differences defined by each model.
Energy supply (refining): The different behavior computed by the models in 2030 and 2050, i.e. increase of CO2 emissions defined by TIMES_PT and a decrease computed by GEM-E3_PT, is explained by the modeling assumptions considered in TIMES_PT in the Baseline and Post-Kyoto scenarios, namely the imposed minimum activity bound to the oil refinery sector (Figure 7). This bound is necessary; otherwise the BU model will shut down the refinery processes, due to cheaper imported refined products when compared to national production. However, the shut-down option is not acceptable due to recent investments in new capacity of the Portuguese oil refinery corresponding to a capacity increase of 29%.

Furthermore, the increase of import prices of refined oil products due to a global/regional Post-Kyoto target will make the national refinery more competitive than what is currently considered in this paper, where such increases were not modeled. Finally, additional model runs showed that in case of absence of a refinery minimum activity bound there are no differences in the behavior of the other sectors meaning that the refinery bound constraint only affects the supply sector.

Commercial sector: CO2 emissions also present relevant differences between the two models, with GEM-E3_PT always reducing more than TIMES_PT throughout all the period of analysis (Figure 7). For example the former achieves a 40% and 91% reduction from 2005 by 2020 and 2050 respectively, while the latter achieves a more modest reduction of 30% and 75% of commercial emissions in 2020 and 2050. Although they reduce different amounts of CO2, both models present the same CO2 reduction strategy, by shifting away from the consumption of oil and natural gas towards more electricity and renewable energy.
GEM-E3_PT reduces the consumption of fossil fuels (gas and oil products) from 36% of total commercial energy consumption in 2005 to 19% in 2020 and 4% in 2050 whereas TIMES_PT moves from a consumption of 35% (without considering renewables) in 2005 to 22% in 2020 and 8% in 2050. Besides fuel shifting GEM-E3_PT makes the commercial sector less energy intensive in average -1.5% per year from 2005 to 2050 while TIMES_PT achieves a more modest reduction of -0.1% per year.

Transport sector: In 2020 both models increase similarly the emissions compared to 2005 (14% more than 2005 in GEM-E3_PT and 11% more in TIMES_PT) (Figure 7). However after that period, the CGE model it is not capable to follow the reduction as TIMES_PT (93% less transport emissions in 2050 than in 2005, i.e. the equivalent to around 16 Gg, whereas GEM-E3_PT reduces only about 8 Gg) (Figure 6). Although both models follow similar reduction strategies through fuel shifts (more electricity in both models and more biofuels only in TIMES_PT) away from oil products, the amount was decided differently. TIMES_PT clearly invested on new transport technologies, migrating from a share of 99% of oil products consumption in 2005 (renewables not included in total final energy for transport) to 8% in 2050, whereas GEM-E3_PT keeps a significant share of conventional mobility technologies, by reducing the 99% share in 2005 to only 52% in 2050.

Electricity generation sector: the emissions differences between the two models are not much significant, with a maximum difference of 3 000 Gg CO\textsubscript{2} in 2050, around 7% of the total national reductions 2050 (Figure 8). In fact both models suggest that the higher absolute reductions will occur in the electricity sector, the main responsible for CO\textsubscript{2} emissions, by shifting to low carbon fuels and an increase of energy efficiency. This is explicit in TIMES_PT with detailed technologies, whereas in GEM-E3_PT the changes in the productive structure of the electricity sector, namely an increase of capital followed by a reduction of energy, suggest a shift to renewable and/or more efficient technologies. In this sense, it should be noted that the much lower energy consumption values for electricity generation estimated by GEM-E3_PT in Figure 8 do not only indicate higher electricity generation efficiency. The renewables consumption in GEM-E3_PT cannot be disaggregated from the increase in other production factors (capital, labour and other materials) and thus cannot be represented in the figure. TIMES_PT increases the share of renewables and the consumption of natural gas, declining coal and oil (Figure 8). While in the Baseline scenario coal plays the main role in electricity generation, in the Post-Kyoto scenario in TIMES_PT the share of coal decreases more than 100% from 2005 to 2050, being zero 2030 onwards. In contrast, GEM-E3_PT keeps using coal, representing a significant difference for future power markets and regulators.
Industry sector: the two models present different reduction paths (Figure 9): until 2030 TIMES_PT reduces the sector emissions more rapidly than GEM-E3_PT achieving in 2030 the maximum cost-efficient industry reductions. In contrast, the CGE model reduces industry emissions gradually accomplishing in 2050 a reduction of 74% compared to 2005 versus 67% in the BU model. According to TIMES_PT and based on its technology database, the chemical industry can achieve zero CO₂ combustion emissions by 2030 through the installation of electricity and biomass based technologies. However given its representation of production technology through production function GEM-E3_PT reproduce a more smooth transition path for this sector, which only starts to reduce its emissions after 2040. This clearly illustrates the potential for divergent industry options and policies within the two models.

For TIMES_PT all industry sectors, both energy intensive (represented by cement, paper, glass and non-metallic mineral products) and non energy intensive (such as electric goods, transport equipment and consumer goods industries), will reduce approximately the same amount of CO₂ over the studied time period. However, in GEM-E3_PT the main contributors for industry reduction are the energy intensive industries, which represent always above 60% of the total industry reduction and in 2030 even reach 82% of this share. Both models achieve this reduction through the decline of fossil fuels contribution to the productive activity of industries. For the non energy intensive industry TIMES_PT computes a reduction of 85% of the total fossil consumption from 2005 to 2050, while GEM-E3_PT stays by the 78%.

Agriculture sector: although the differences between the two models are extremely high, above 200%, with the CGE model reducing more than TIMES_PT, they represent a relatively low contribution to achieve the national target since the share of CO₂ combustion emissions from agriculture is relatively small (2% of the total CO₂ emissions in 2005 and 2% in 2020 and 2050 in the Baseline scenario.

One way to evaluate the economic impact of a climate policy is through the welfare losses, represented by the changes in consumer/producers surplus. As already mentioned in the literature, in the present analysis GEM-E3_PT has estimated a higher cost to achieve the Post-Kyoto level of abatement: 13% of welfare losses versus the 8% estimated by TIMES_PT. This difference is confirmed by the divergences regarding the CO₂ marginal abatement costs calculated by the models.
TIMES_PT achieves a marginal abatement cost in 2020 around 46€/ton CO\textsubscript{2} while GEM-E3_PT computes a value more than twice higher.

Globally, one can state that for lower reduction efforts both models can suggest similar strategies to reduce CO\textsubscript{2} in the EU-ETS and Non EU-ETS as it can be seen in 2030. However for higher caps the models assume different strategies with TIMES_PT applying a bigger effort in the Non EU-ETS sector and GEM-E3_PT keeping the EU-ETS higher effort. Also, at sectoral level, the models results in different amount of CO\textsubscript{2} reductions especially for transport and industry, suggesting divergent cost-effectiveness, with potential implications for these sectors when designing policy instruments.

6. Conclusions

This paper aims to evaluate if a CGE and a BU model can result in different strategies for CO\textsubscript{2} reduction, with implications in the development of mitigation policies using the Portuguese economy and respective energy system as a case study. Comparability of the models results were assured through a calibration process defining an equal Baseline scenario in the absence of climate policies and in terms of sectoral energy consumption and CO\textsubscript{2} emissions. A CO\textsubscript{2} reduction scenario (Post-Kyoto scenario) was established in line with the European carbon reduction targets being discussed for 2020 and 2050.

Results show that in general the models can point out to the same direction, assigning the larger mitigation potential, in absolute terms, to electricity generation, industry and transport. For lower reduction efforts, which can be met without significant changes in the energy system structure, the models indicate roughly the same strategy regarding the whole EU-ETS and Non EU-ETS sectors. However in terms of relative CO\textsubscript{2} mitigation for stringent reduction efforts the BU and CGE models indicate different reduction potentials for these two pollutant groups and the sectoral differences within each can be important. This has implications especially if a burden-sharing agreement is being considered, leading to different sectoral carbon reductions caps and impacts. The differences may induce policy makers in selecting dissimilar sectoral policies and instruments for mitigation.

For example looking to TIMES_PT results policy makers can be persuaded to adopt additional measures to achieve a higher transport reduction, while looking to GEM-E3_PT suggests that transport is one of the sectors that has smaller potential for cost-effective reduction, while the commercial sector is appealing. Or following TIMES_PT results policy makers can decide that industry should reduce emissions only until 2030 while it is cheaper, whereas GEM-E3_PT suggests industry reductions have the same cost-effectiveness during the whole studied period. Furthermore, although both models agree on the magnitude and relevance of the role of the power sector and on shifting fuels to reduce emissions, the indication on how to exactly get there differs. While GEM-E3_PT maintains some coal for electricity generation, in TIMES_PT this fuel is completely substituted by gas and renewables. Finally, although globally both models follow the same reduction approach of fuel switching, there is a relevant exception of the reduction of industrial activity in response to the CO\textsubscript{2} cap which is only adopted in GEM-E3_PT. TIMES_PT, due to the higher technological flexibility is capable of meeting the cap without reducing industrial production.

The discrepancies in model results are relevant not only regarding effort-sharing of reduction but also in setting the global reduction targets if parameters as marginal CO\textsubscript{2} abatement costs or welfare losses are used. While TIMES_PT estimates a marginal abatement cost in 2020 of around 46€/ton CO\textsubscript{2} GEM-E3_PT estimates a value more than double. Similarly, GEM-E3_PT defines 13% of welfare losses to achieve the Post-Kyoto scenario cap in 2050, whereas TIMES_PT estimates only 8%. Such parameters are frequently used by policy-makers in climate negotiations and the differences obtained between models can steer them in different directions. The higher values of the CGE model are in line with the literature findings. However, it is interesting to ascertain exactly how big is the difference for the Portuguese case.

The divergences between models results are related to their technical representation: CGE substitution elasticities give a more smooth reduction path while TIMES-PT reduction path reflect the explicit penetration of technologies and therefore can go as far as the available technology database allows for. This happens for example in the electricity generation sector where GEM-E3_PT, through its production function, cannot stop the use of coal completely. On the other hand,
even considering exogenous price elasticities for the demand TIMES_PT cannot replicate the full economic feedback defined by GEM-E3_PT.

Further work will be undertaken to enhance the consistency between the two models, namely by harmonizing the substitution possibilities between energy sources, i.e., defining substitution elasticities for the TD model that “replicate” more properly the technology choices of the BU model.

Ongoing developments include the implementation of a link between the models that covers all sectors, particularly industry and electricity generation and not just for transportation or households as was made by Schäfer and Jacoby (2005) and Drouet et al. (2005). Moreover we analyze how the conclusions obtained by the linked model diverge from the ones of the separated but harmonized models.

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8. References


